Status of the CMS Phase 1 Pixel Upgrade

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on behalf of the CMS Tracker Collaboration

Technology and Instrumentation in Particle Physics (TIPP'14)

03.06.2014

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DESY

PHYSICS AT THE TERA SCALE Helmholtz Alliance

Outline

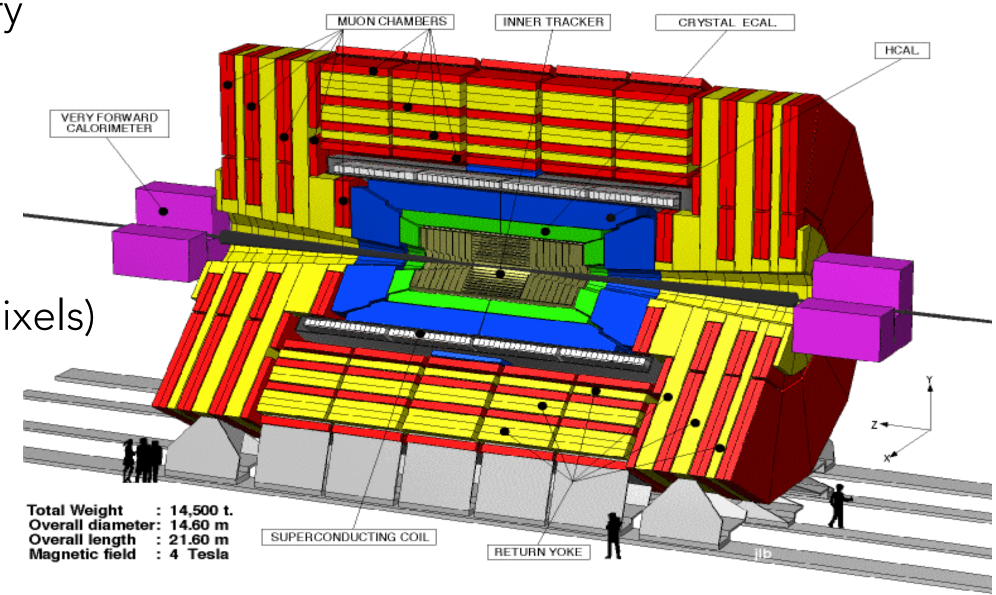
- The CMS Pixel Detector & Motivations for the Upgrade
- Module Production Steps (in Hamburg)
- Qualification of Single-Chip Modules
    - DESY Test Beam & X-ray Studies
- General Status and Outlook

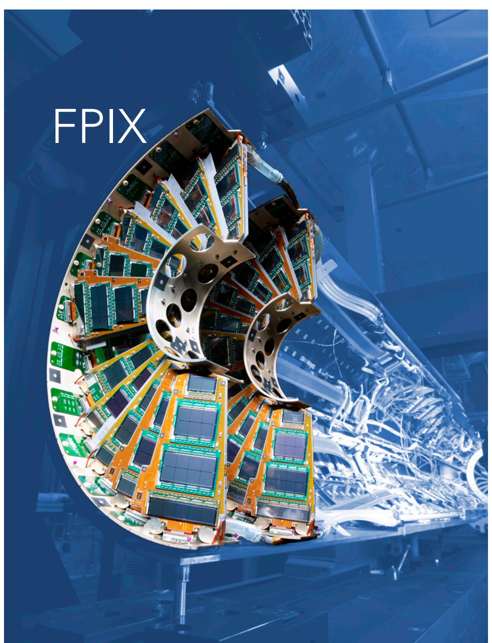
CMS Pixel Detector

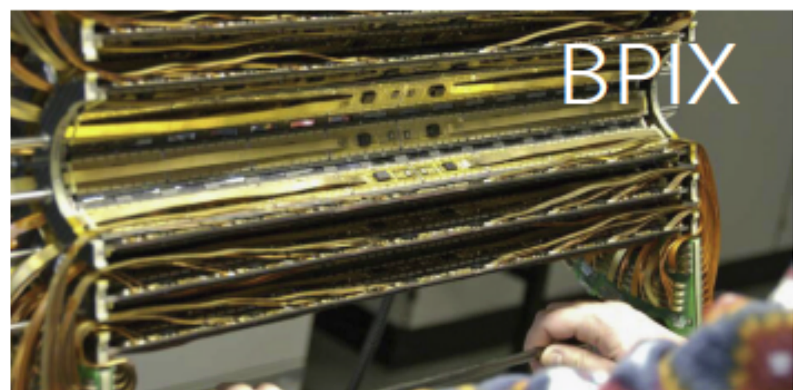
- Innermost component of the CMS tracking system
- Crucial role in full tracking, primary/secondary vertexing, b-tagging, e/γ separation,…

Presently installed system:

- 3 layers in the barrel (BPIX, 48 M pixels)
- 2+2 disks in the forward region (FPIX, 18 M pixels)
- Resolution in rϕ~9 μm and in z~20 μm

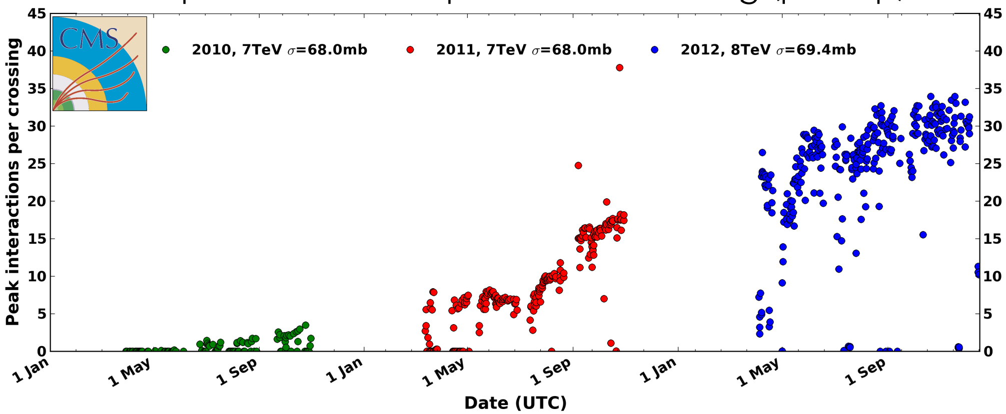


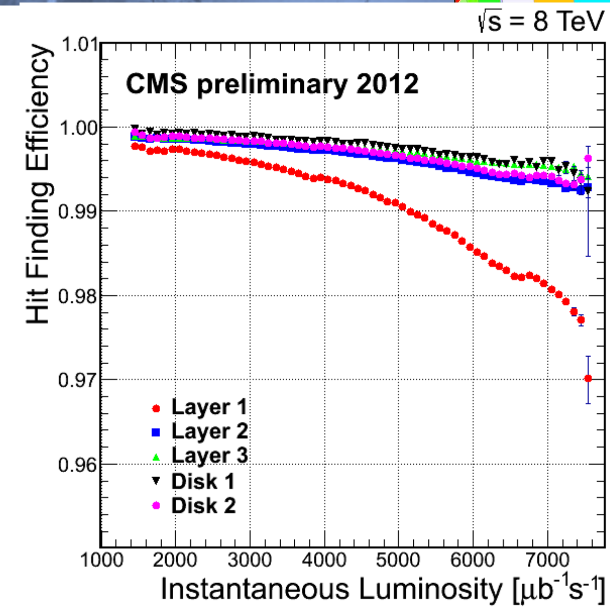




Challenges and Upgrade Plans

Multiple interactions per bunch crossing (pile-up)





- Present pixel tracker designed for maximum $L_{inst}=1\text{x}10^{34}\ cm^{-2}s^{-1}$
  → expected in 2015!

- Likely to reach $L_{inst}=2\text{x}10^{34}\ cm^{-2}s^{-1}$ before 2018 → Expected inefficiency for Layer 1:
  bunch crossing frequency 25 ns: 16%
  bunch crossing frequency 50 ns: 50%

Data loss mainly due to:
- Overflows of buffers in the Readout Chips (ROC)
- Saturation of data links

Degradation of spatial resolution due to radiation damage in the sensor

Replace entire pixel detector in winter-shutdown 2016/17

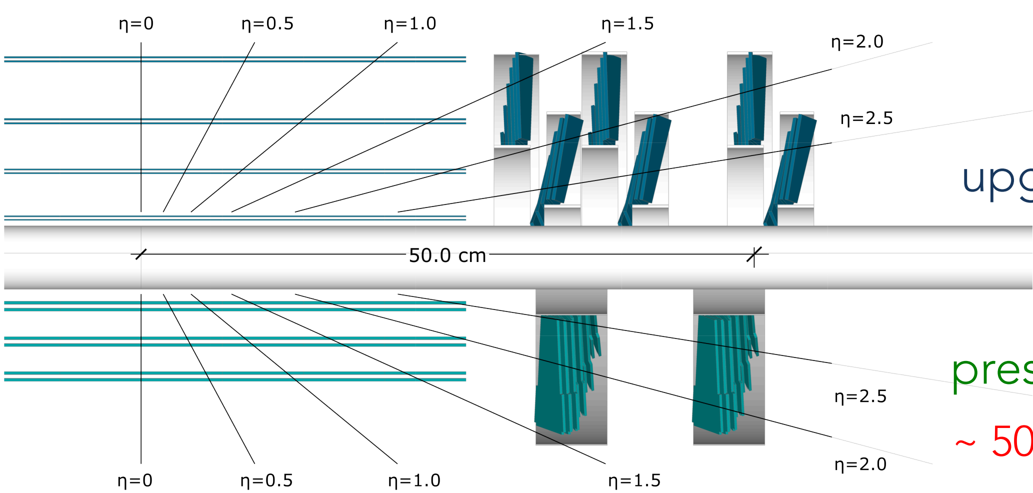
The Upgrades

One layer more with respect to the current detector (BPIX and FPIX)
→ Improved efficiency and resolution

Increased buffers on the readout chip
→ Improved efficiency at high fluxes

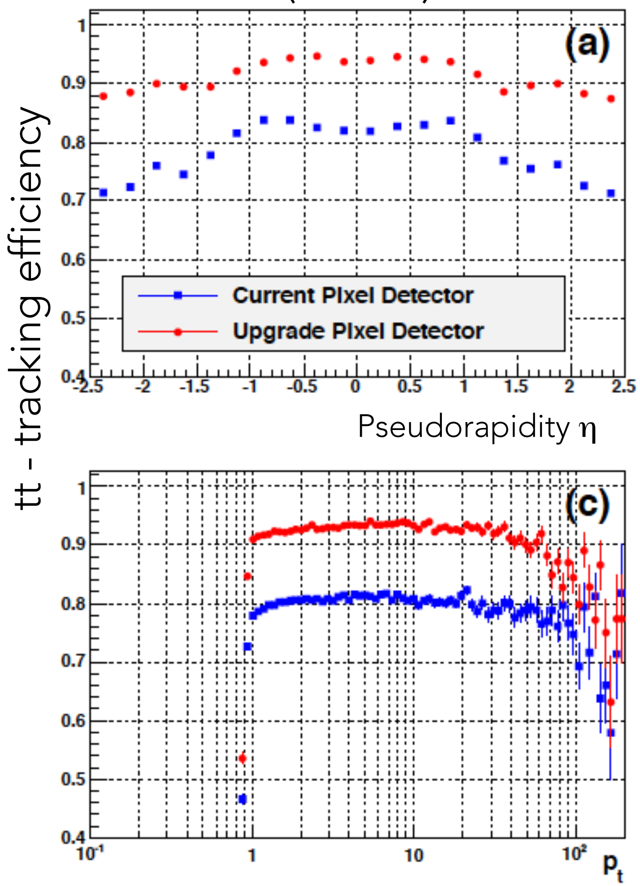
Digital output from the readout chip
→ Gain in communication speed

CO_2 cooling, new cabling and powering scheme (DC–DC)
→ Less material

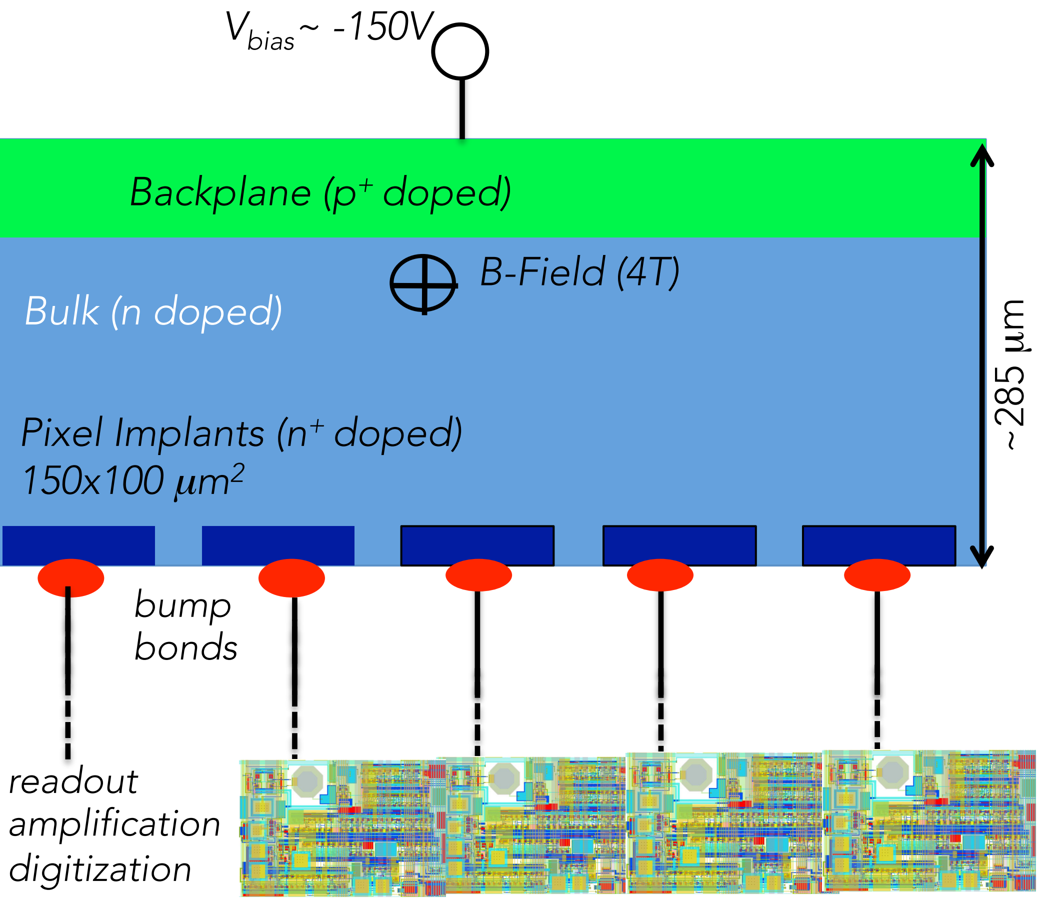


~ 50% more pixels!

L=2×10^{34} $cm^{-2}s^{-1}$ @ 25ns
(PU=50)



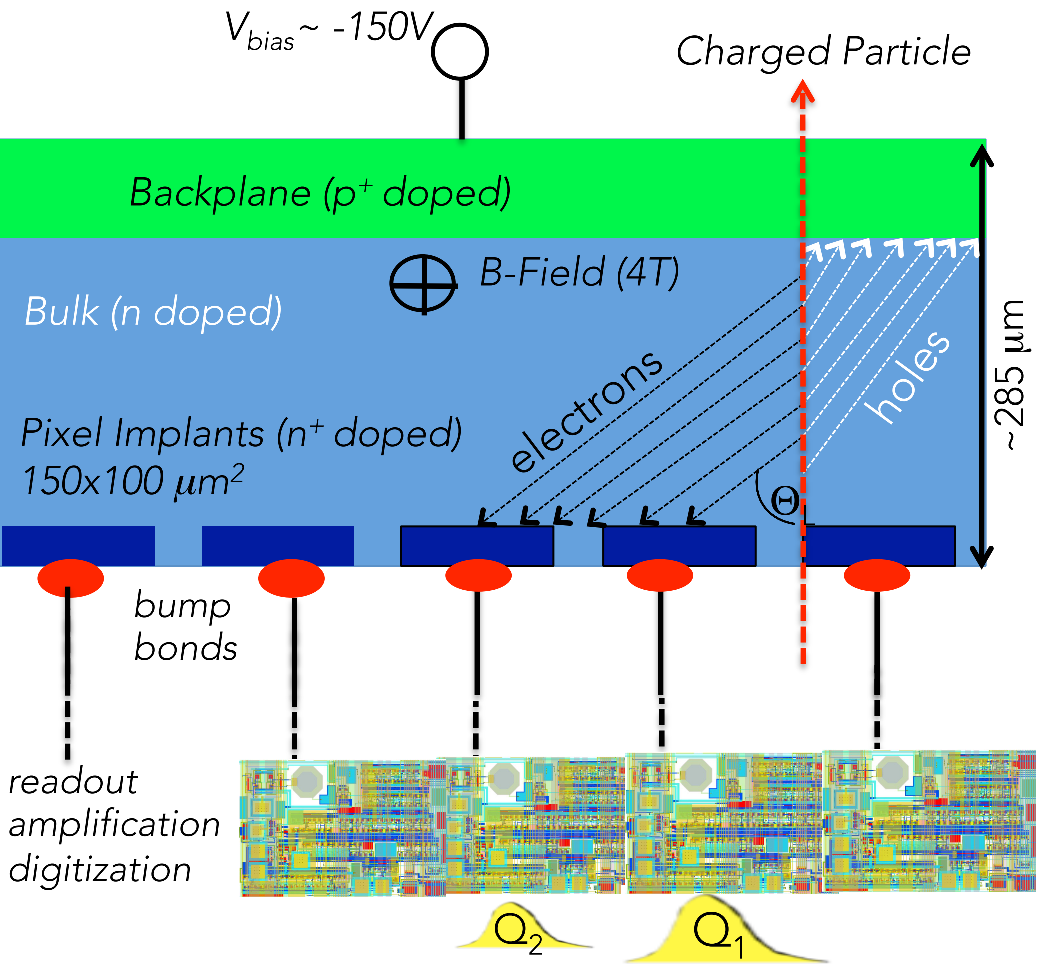
CMS Pixel Sensors



"n^+ in n" design

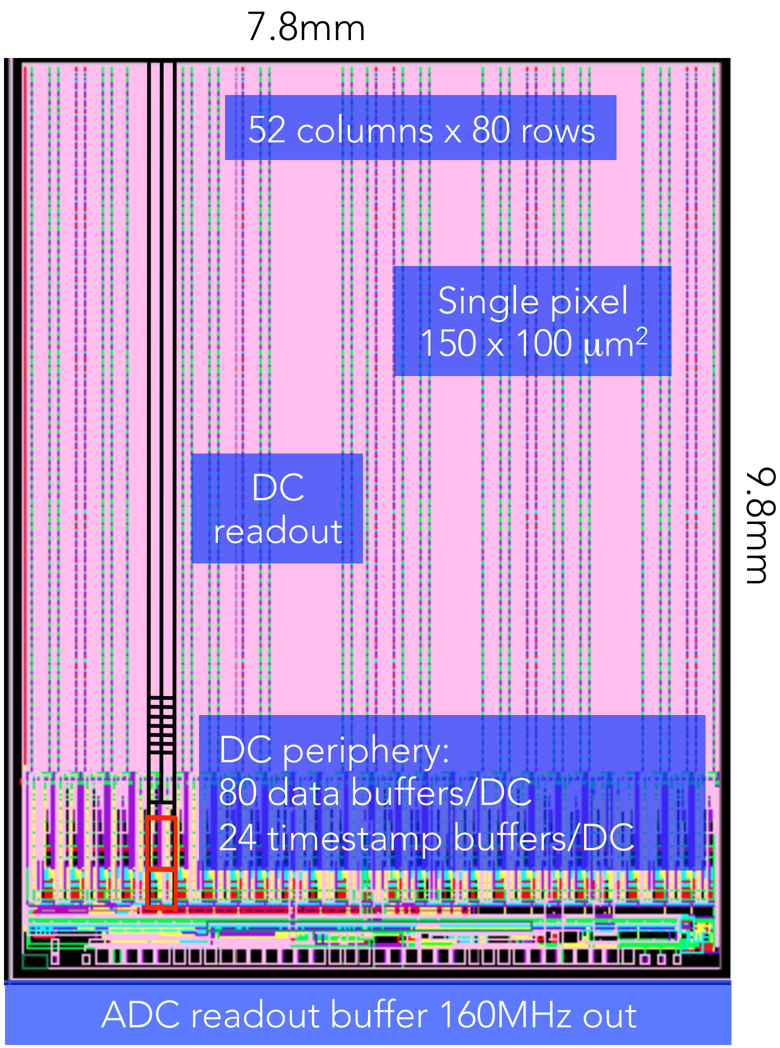
- Pixel size 150x100 μm^2
- 285 μm thick
- Each pixel is bump bonded to it's readout

CMS Pixel Sensors



- Signal charge is deflected by magnetic field and shared among pixels ~Θ_L=18°
- Analog charge interpolation among pixels "center of gravity" → improves resolution
- Sensor shown to be sufficiently radiation hard → design kept for upgrade

ROC Upgrade



- 4160 pixels, bump-bonded to sensor
- Double columns (DC) operate independently
- Zero suppressed charge stored in periphery buffers
- Trigger verifies hits are readout after external token passage

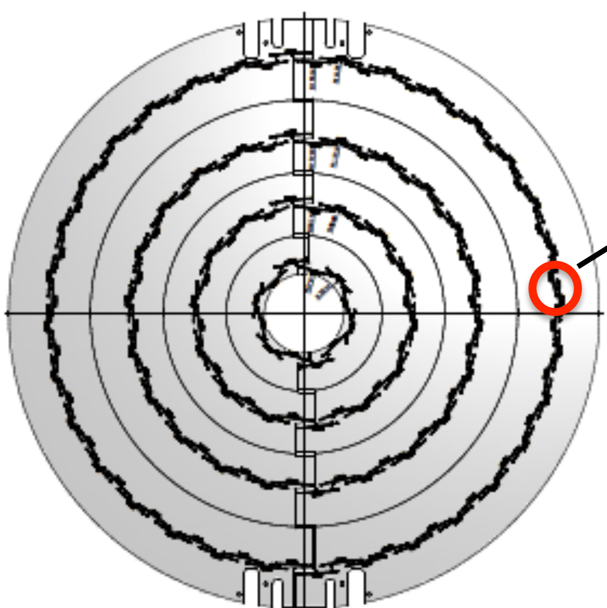
<u>Upgrade improvements:</u>

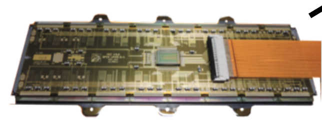
- Increased data and timestamp buffers
- Additional readout buffer stage
- Additional ADC, increased readout link speed
  40MHz analog → 160MHz digital
- Enhanced analog performance:

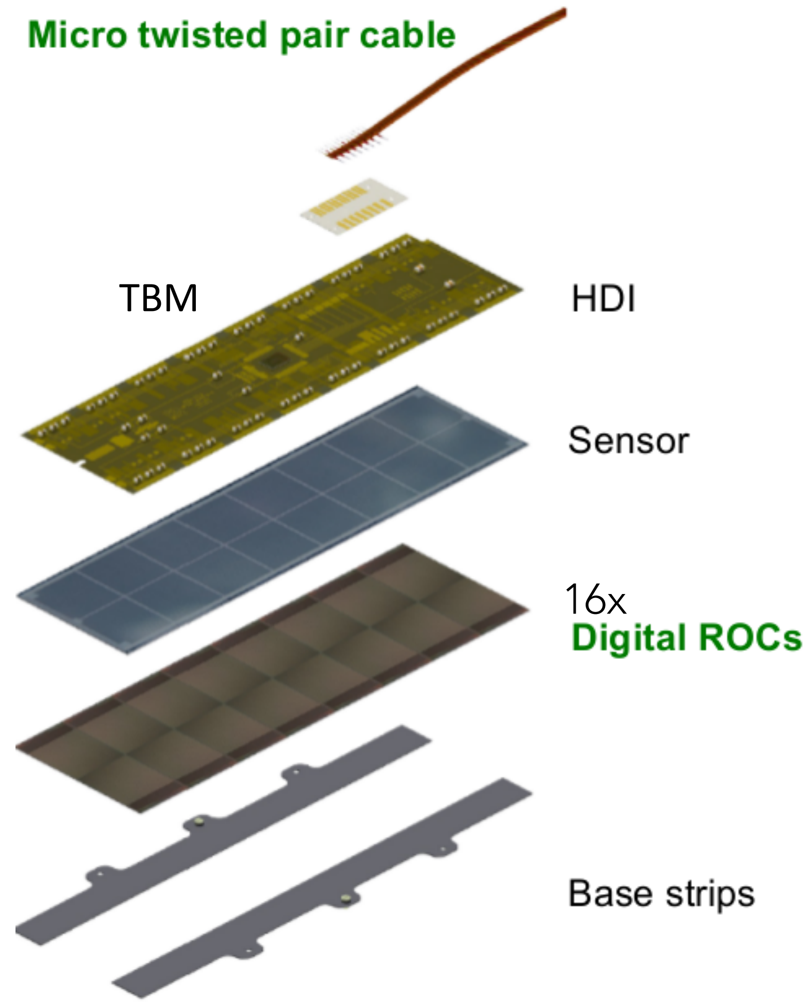
→ Charge threshold reduced: 3.5 ke to 1.5 ke

CMS Barrel Pixel Modules

Layer	Radius [mm]	# Modules	Production Centers
1	29	96	CH (PSI)
2	68	224	CH (PSI)
3	109	352	CERN, IT, TW, FI
4	160	512	GER. KIT/Aachen + DESY/UHH



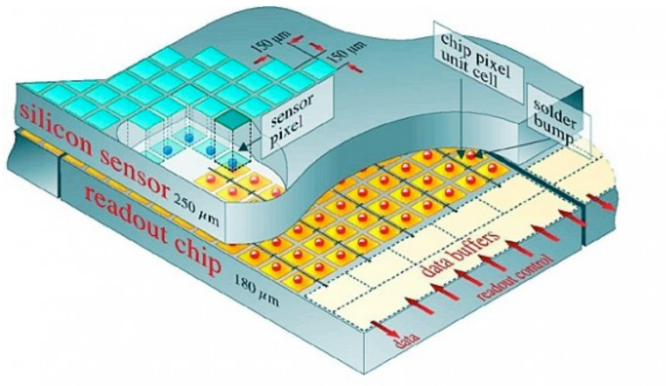




Module Production at DESY/UHH

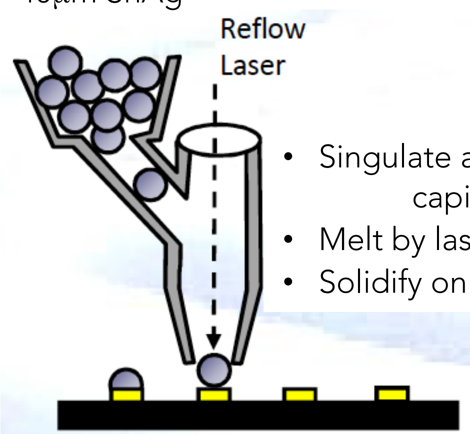
Sensors

Bump Deposition
"solder jetting"

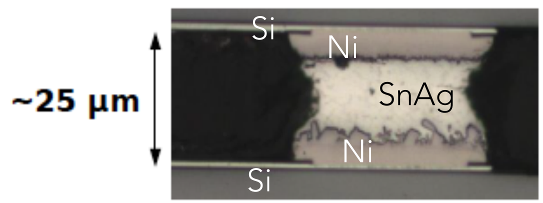


ROCs

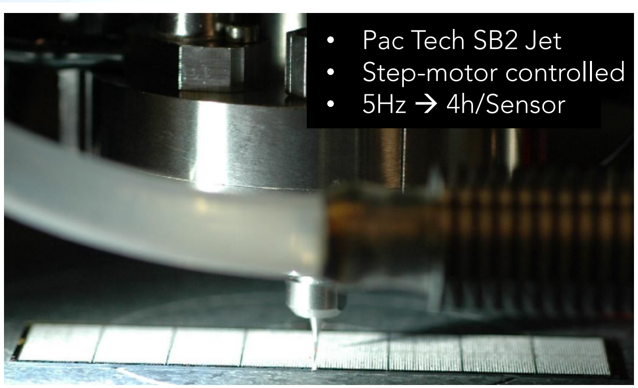
Solder balls
40µm SnAg



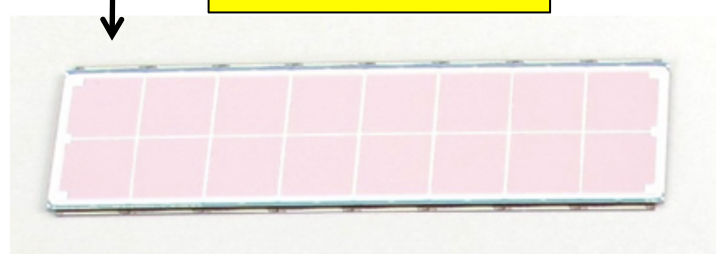
- Singulate and drop through capillary towards pad
- Melt by laser pulse during fall
- Solidify on pad



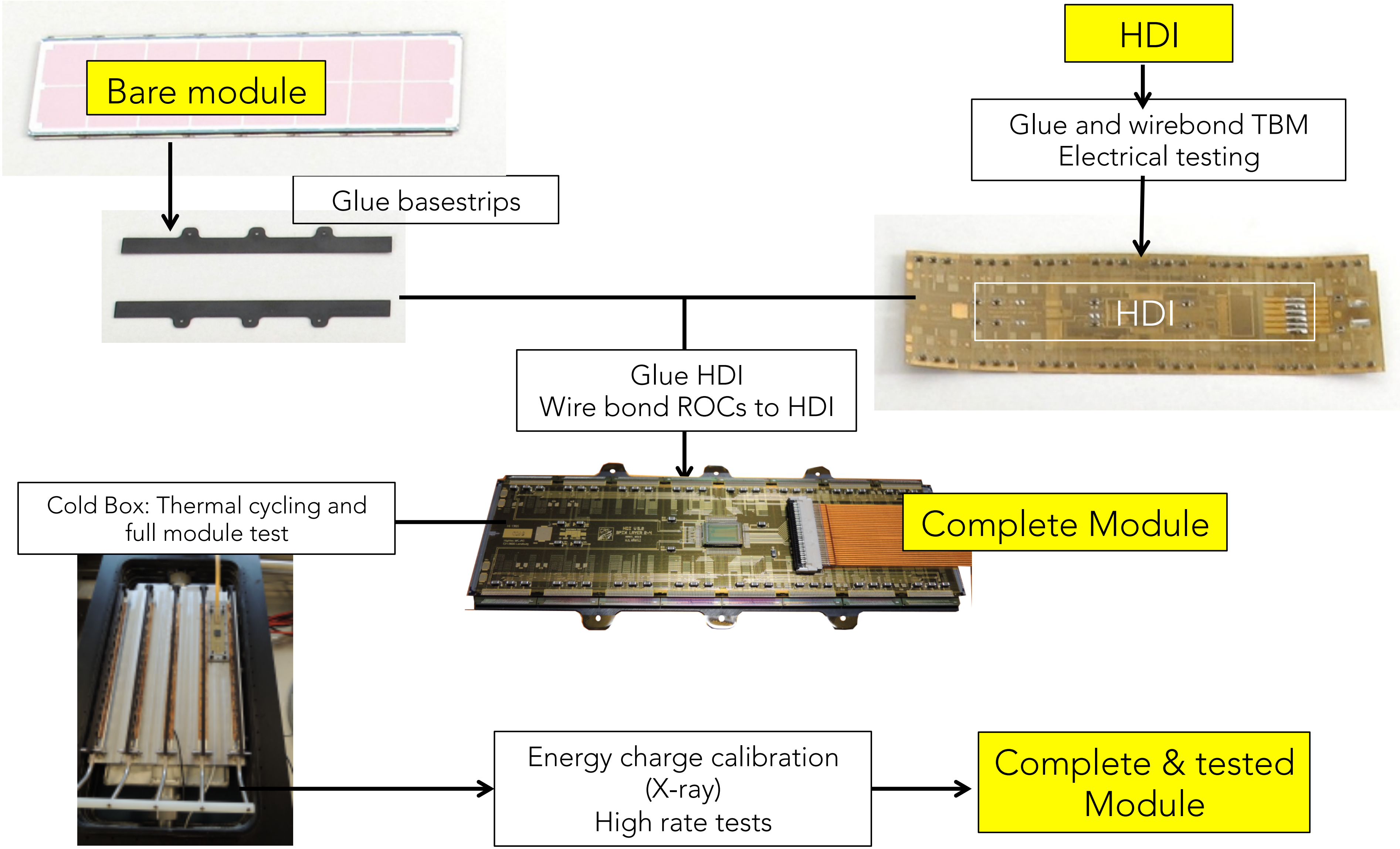
Flip chip bonding



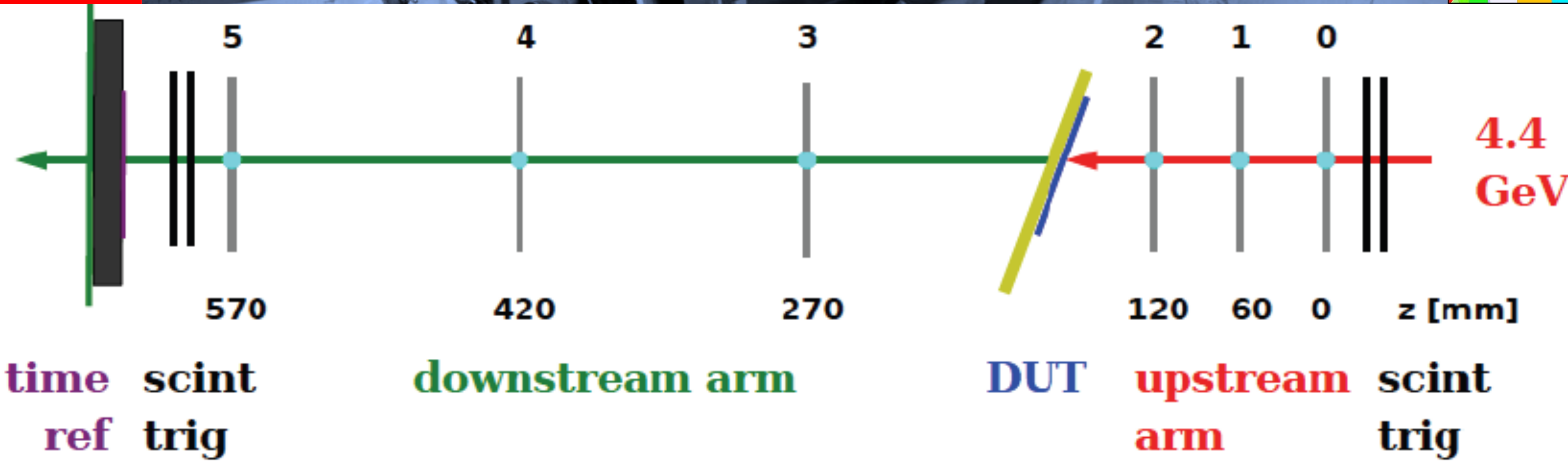
Bare module



Module Production at DESY/UHH



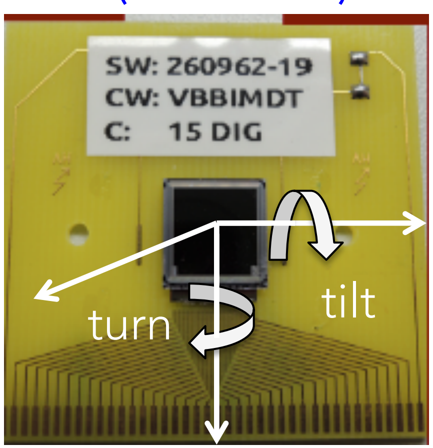
DESY Test Beam



Qualification of module prototypes in the test beam

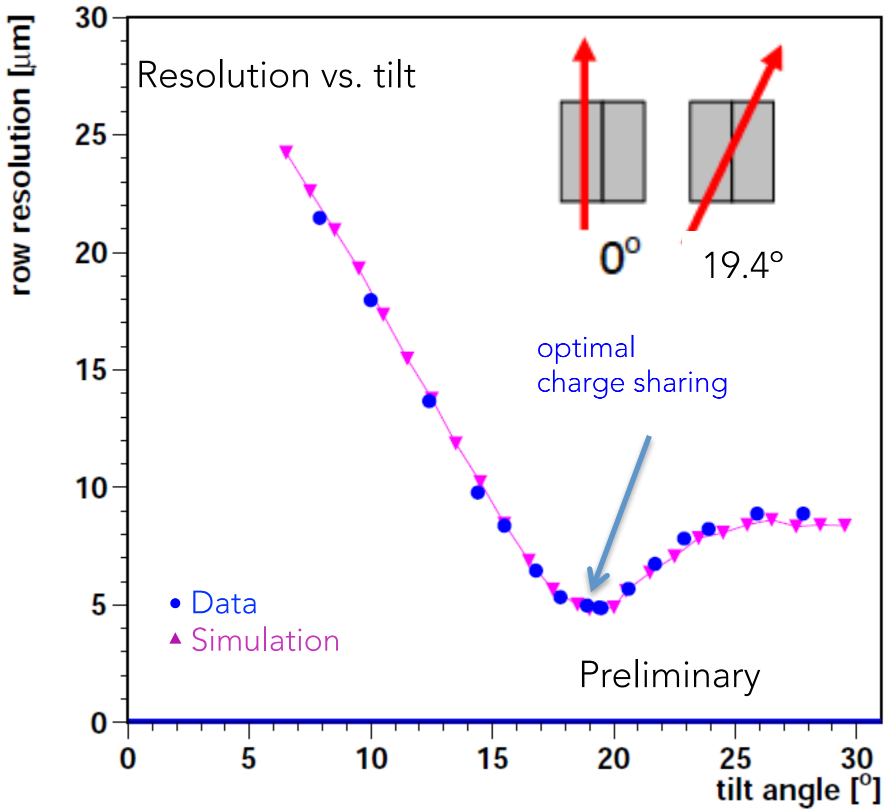
- Telescope[*]: 6 planes of Mimosa26 (MAPS) devices
- Beam: ~$\mathcal{O}$(kHz/cm^2) of 1–6 GeV $e^\pm$
- Device under test (DUT): Rotatable (tilt/turn)
- REF = single chip module for timing
- Trigger: 4-fold scintillator coincidence

DUT: Single chip module (ROC+sensor)

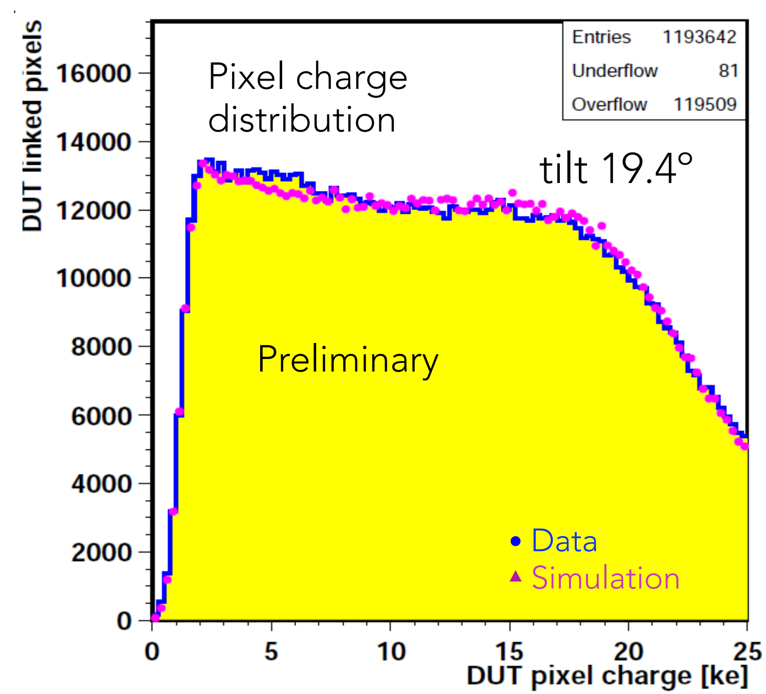


[*] See also at TIPP'14:
http://indico.cern.ch/event/192695/session/7/contribution/347
http://indico.cern.ch/event/192695/contribution/345

Test Beam and Simulation



- Single chip module (sensor bump bonded to read out chip)
- Threshold ~1.5ke
- V_{bias} -150V

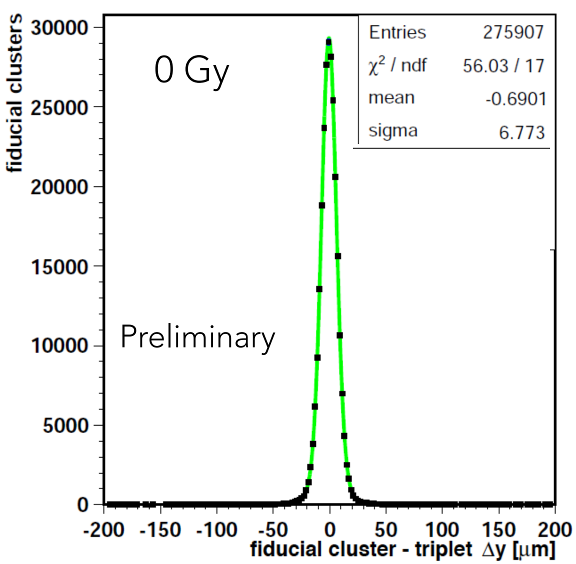


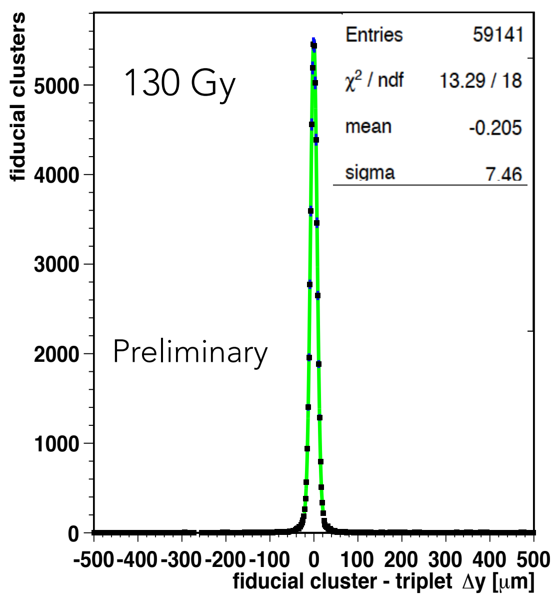
After subtracting the telescope resolution:
Spatial resolution ~ 5.1 μm

Irradiation Studies

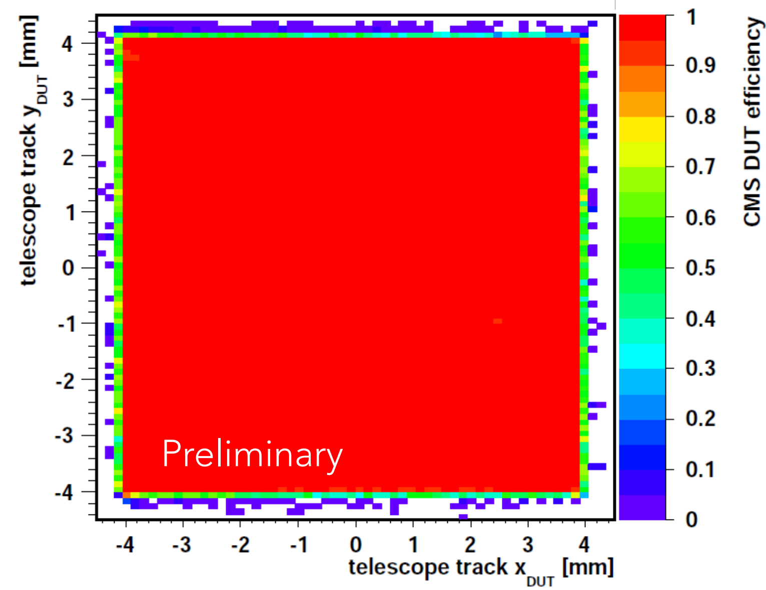
Irradiated at CERN PS with 24GeV protons
ϕ= 3.77 x 10^{14} p/cm^{-2} → 130 kGy
(Full layer 4 lifetime dose)

Threshold: ~1.5 ke
Full depletion at V_{bias} = -200 V





Efficiency map

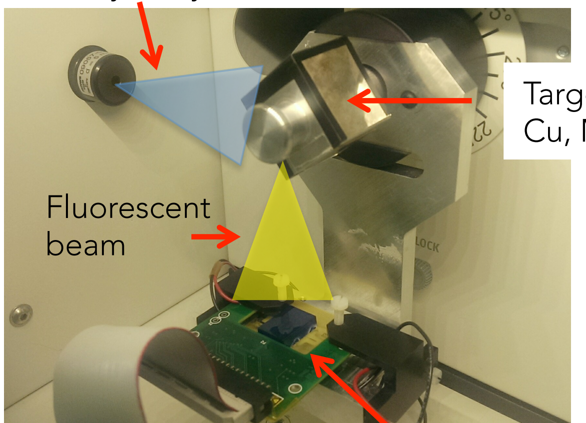


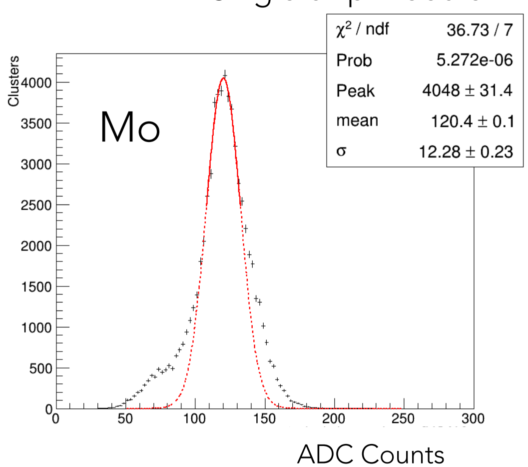
Remains 99.8% efficient in fiducial volume

After Irradiation: Spatial resolution ~6.2 μm (before ~5.1μm)

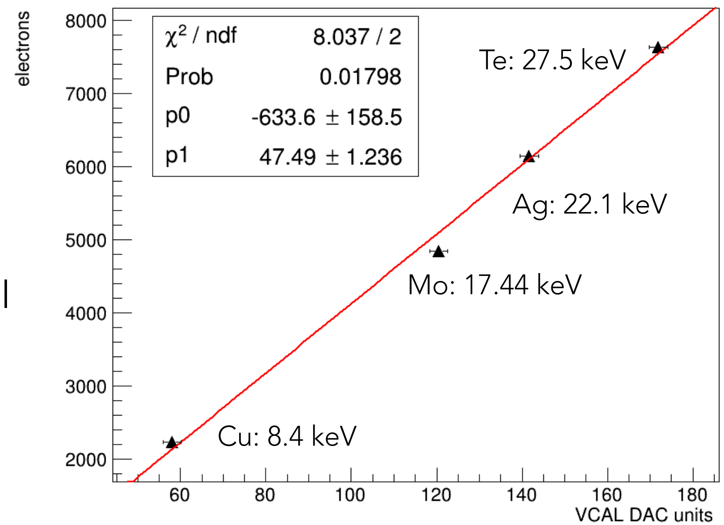
X-Ray Calibration of Internal Test Pulse

- To perform tests of the readout chain, and for setting the thresholds, an internal calibration pulse (Vcal) is used
- Absolute energy calibration is performed using well defined x-ray fluorescence lines





Relate internal Vcal unit to well known charge deposition of X-Rays



Calibration line → ~50 e^- per Vcal

Summary & Outlook

- CMS will replace the pixel detector during the extended year end technical stop in 2016/2017:
  - 4 barrel layers and 3 forward disks
  - New digital read out chip

→ Maintain/improve performance of current pixel detector at large pile-up

- ROC prototype works very well and with expected performance (also after irradiation)

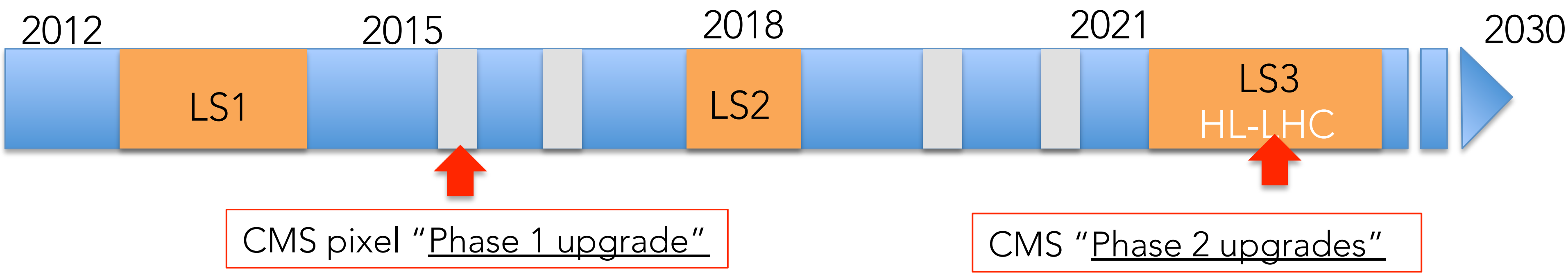
- Sensors produced, ROC submissions at hand

→Module production will start in fall!

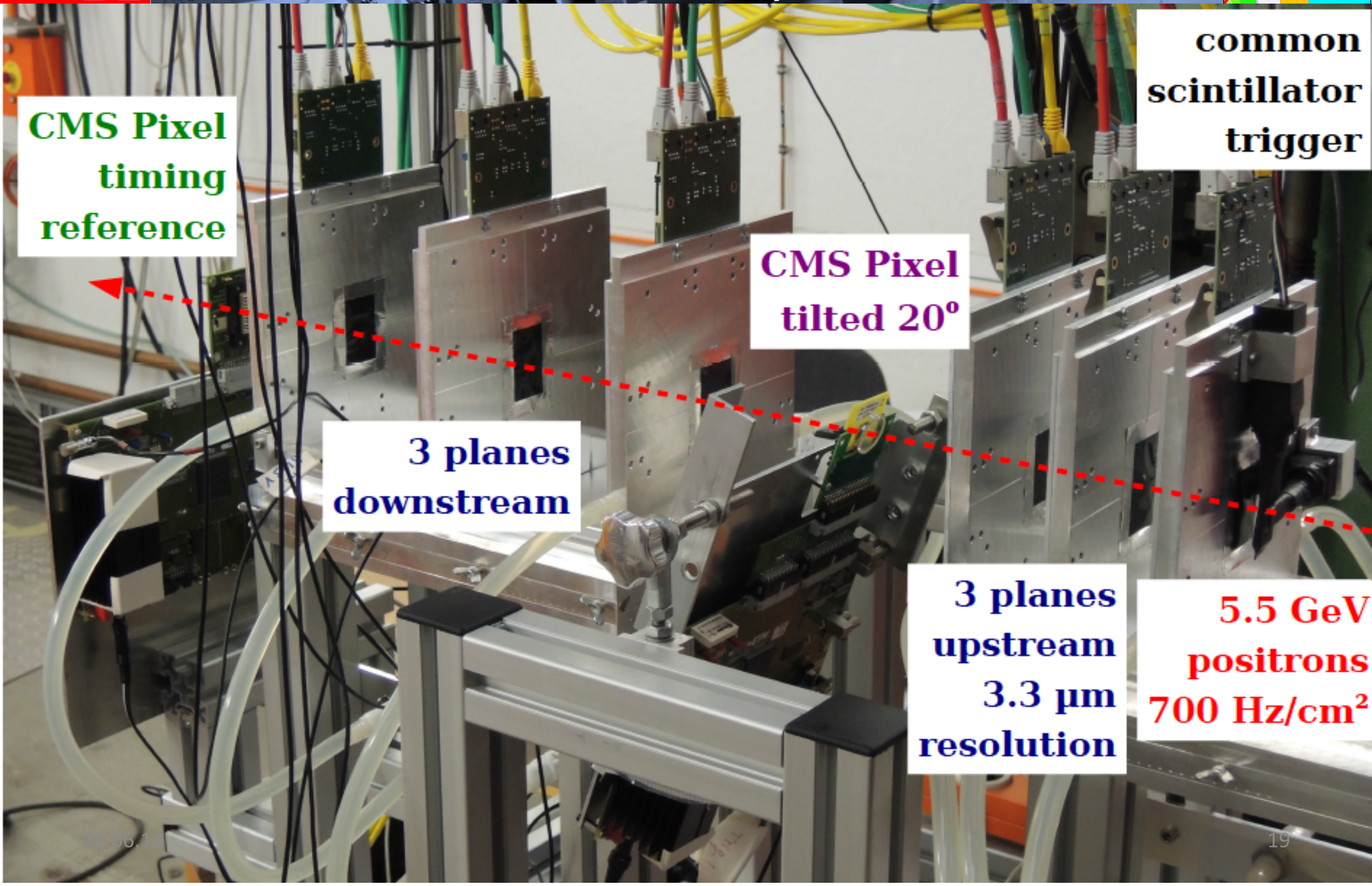
CMS Technical Design Report for the Pixel Detector Upgrade
http://cds.cern.ch/record/1481838?ln=de

BACKUP

BACKUP


2012
2015
2018
2021
2030
LS1
LS2
LS3
HL-LHC
CMS pixel "Phase 1 upgrade"
CMS "Phase 2 upgrades"

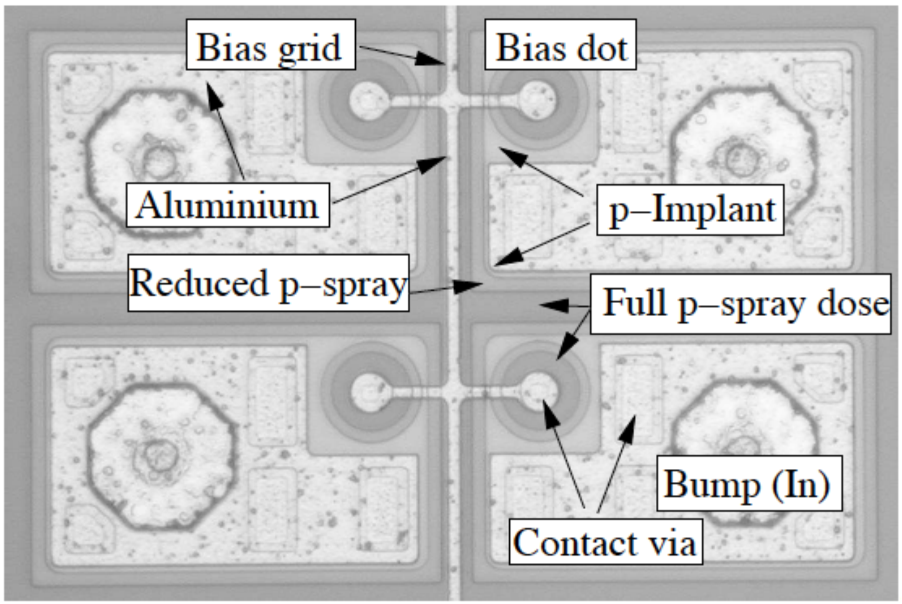
CMS Pixel in the DESY Telescope

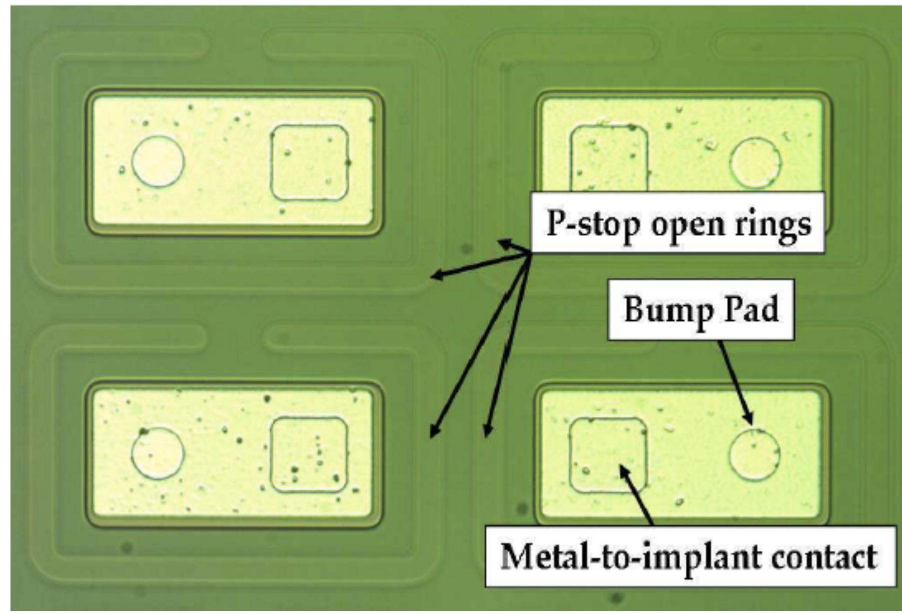


BACKUP

Parameter of Pixel System	*Present*	*Upgrade*
# layers (tracking points)	3	**4**
beam pipe radius (outer)	29.8 mm	22.5 mm (LS1)
innermost layer radius	44 mm	29.5 mm
outermost layer radius	102 mm	160 mm
pixel size (r-phi x z)	100μ x 150μ	100μ x 150μ
In-time pixel threshold	3400 e	1800 e
pixel resolution (r-phi x z)	13μ x 25μ	13μ x 25μ (or better)
cooling	C_6F_{14} (monophase)	CO_2 (biphase)
material budget X/X_0 (η=0)	6%	5.5%
material budget X/X_0 (η=1.6)	40%	20%
pixel data readout speed	40MHz (analog coded)	400Mb/sec (digital)
1^{st} layer module link rate (100%)	13 M pixel/sec	52 M pixel/sec
ROC pixel rate capability	~120 MHz/cm^2	~580 MHz/cm^2
control & ROC programming	TTC & 40MHz I^{2}C	TTC & 40MHz I^{2}C

CMS Pixel Sensor



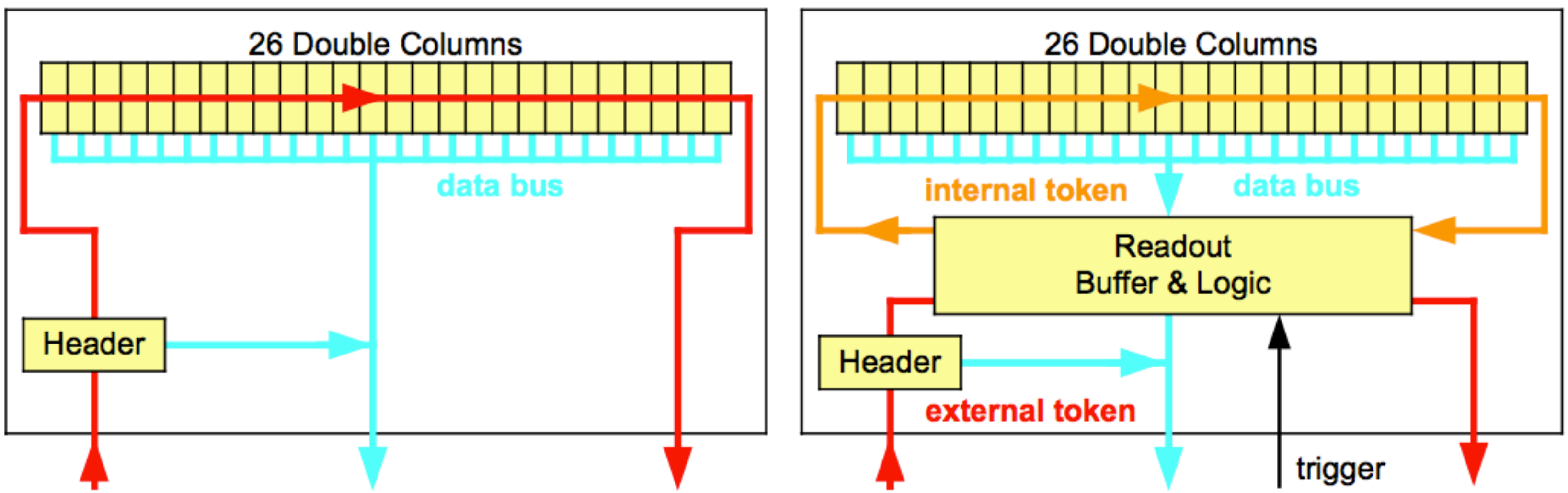


New Readout Chip

Increased buffers in the double column periphery:

- time-stamp 12 → 24
- data-buffers 32 → 80

In addition: **present ROC** **new ROC**



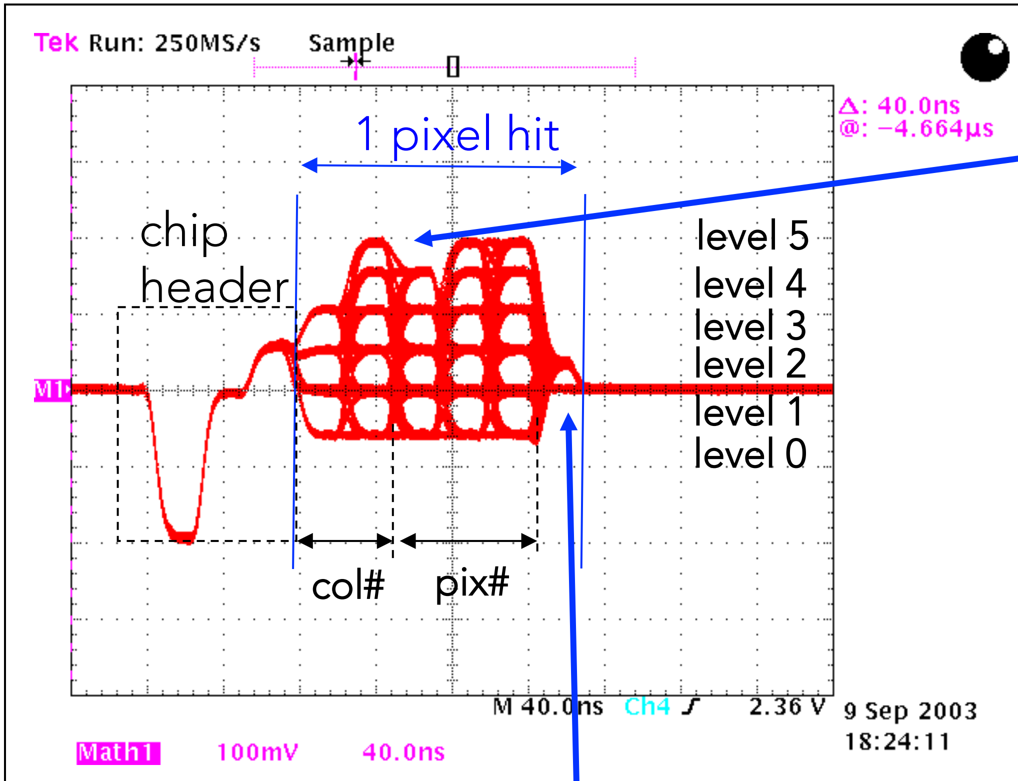
Trigger verified data has to wait for external token passing through all ROCs and Double Columns
During this time Double Columns are blocked for data taking

New readout buffer with 64 cells added:

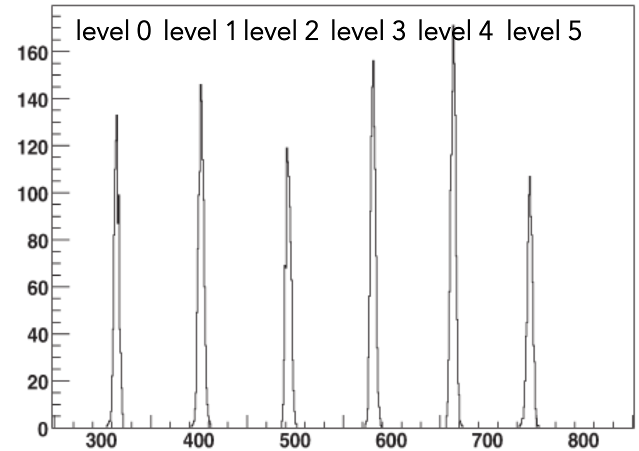
If trigger arrives double column buffers can be copied to new FIFO and double column can resume data taking

ROC "Digital Coded" Analog Readout

Scope overlap of 4160 pixel readouts



5 clock cycles:
encode 13 bits of pixel address information.

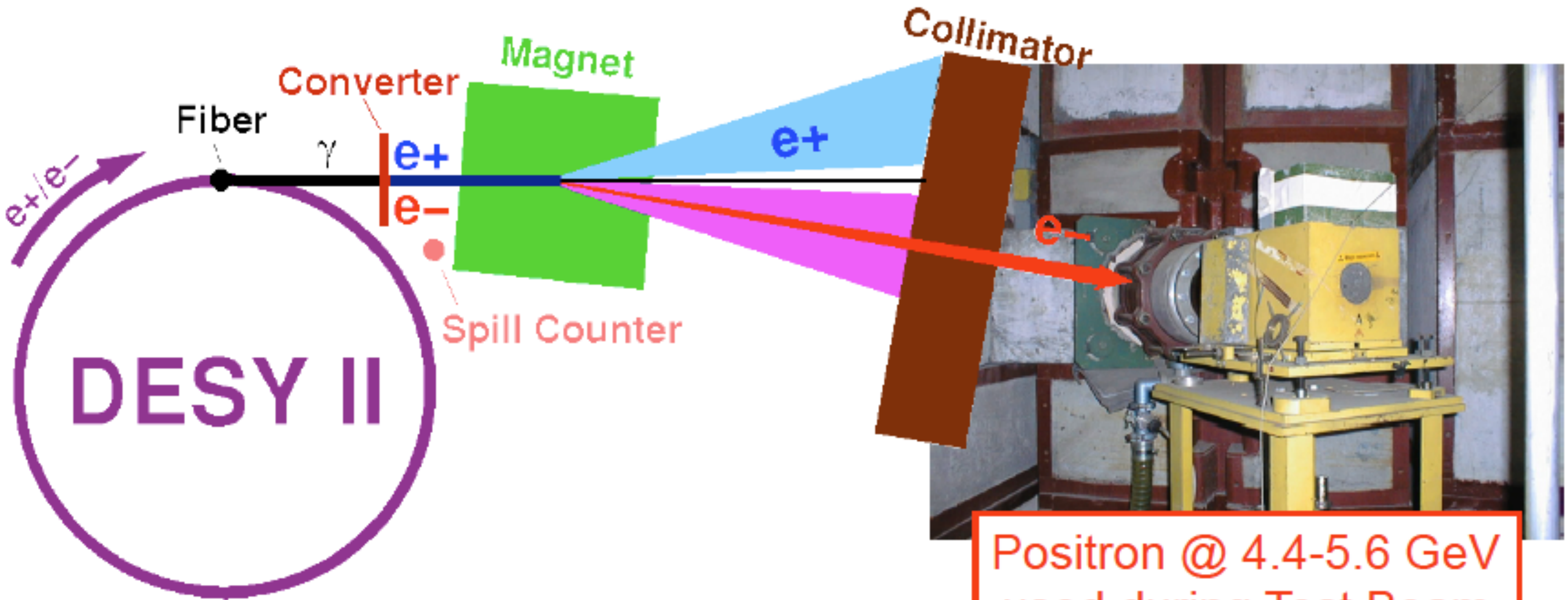


Address level histogram as received by the FED where it is digitized. Robust decoding is possible with the RMS to distance ratio of 26:1.

1 clock cycle:
analog pulse height

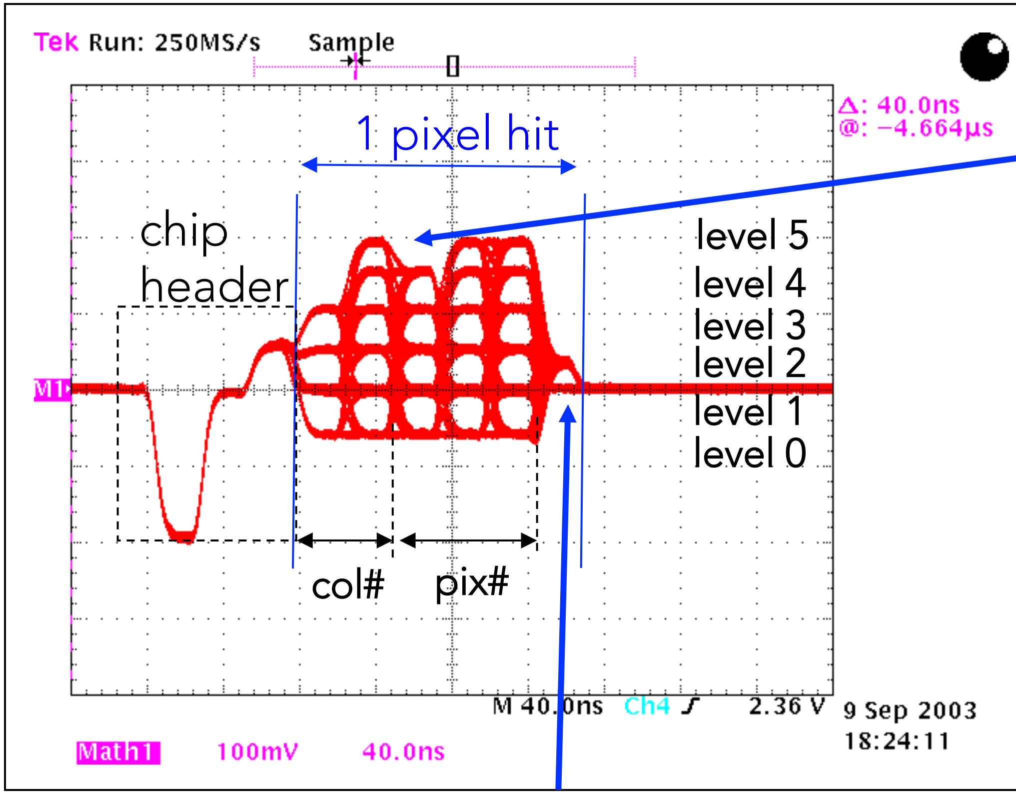
The output levels can be adjusted by DACs in each chip to reduce chip-to-chip variations. In addition, the level decoding by the FED is calibrated on a per chip basis.

DESY Testbeam Setup

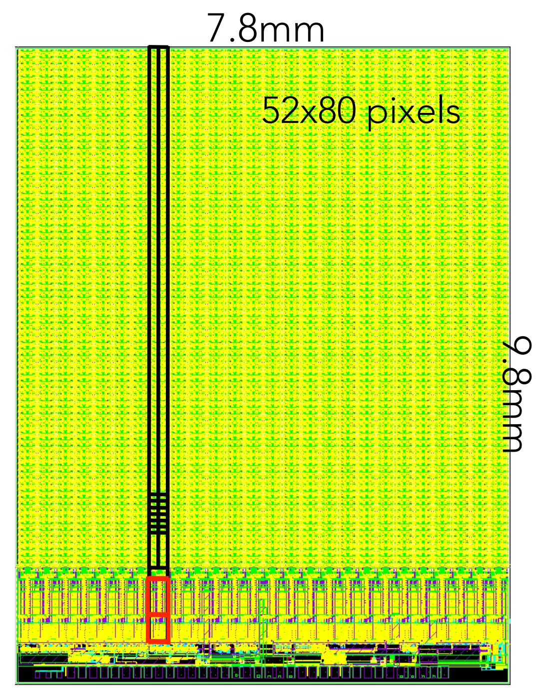


Positron @ 4.4-5.6 GeV used during Test Beam operation

Scope overlap of 4160 pixel readouts

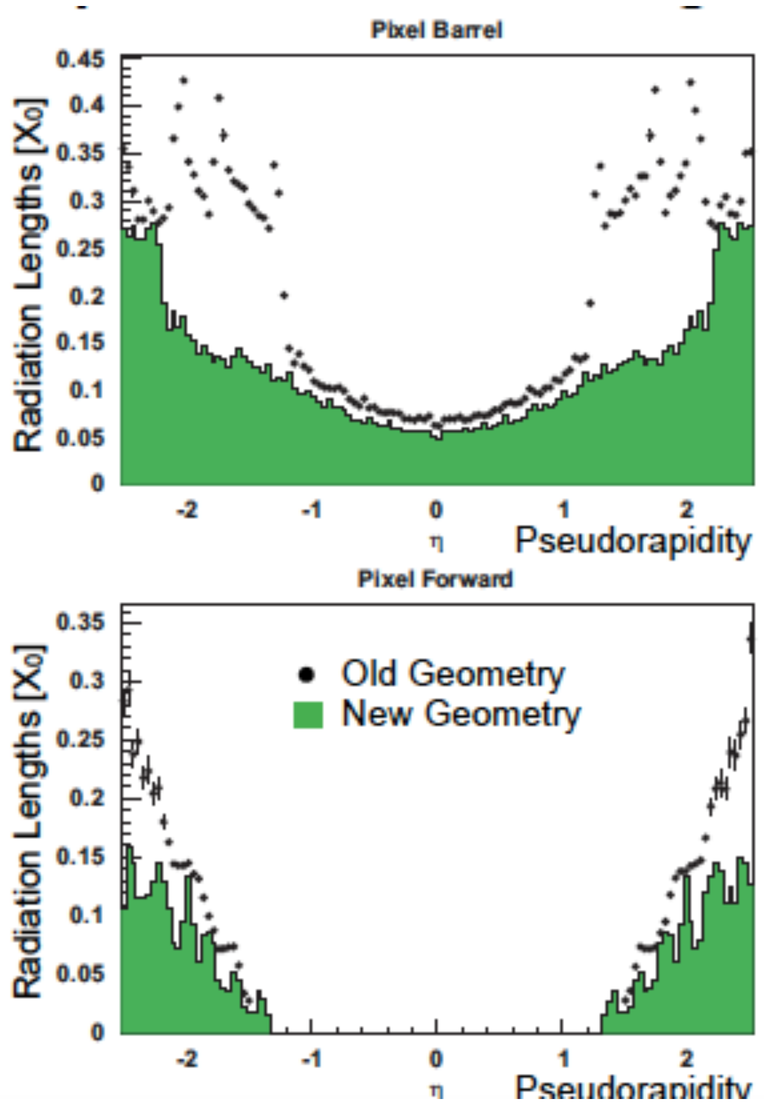


5 clock cycles:
encode 13 bits of pixel address information.



1 clock cycle:
analog pulse height

Material Budget

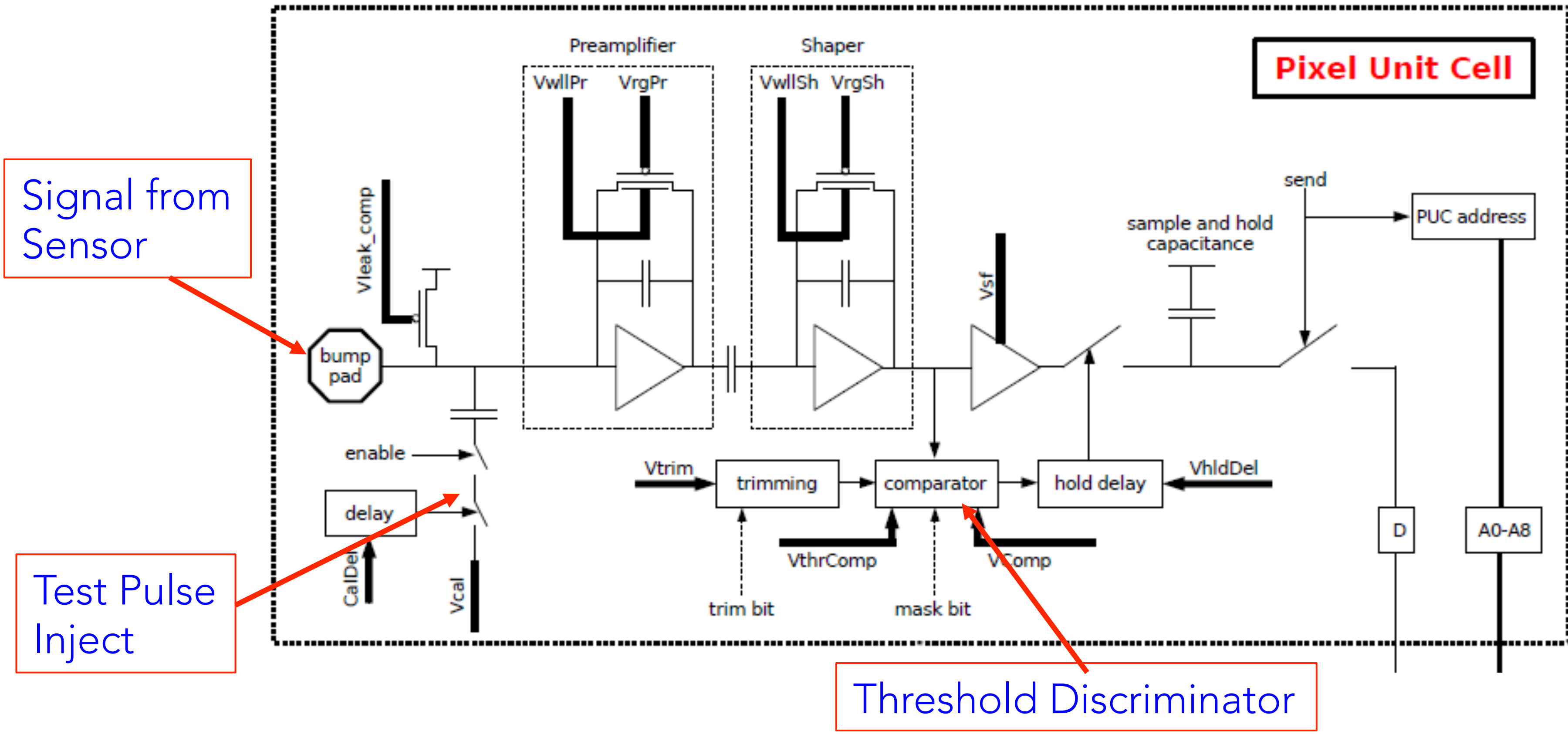


[A. Bean, NIM A650 (2011) 41]

- Central part (|η|<1.1): new four-layer detector with less material than old three-layer detector
- Forward part: shifting of services on support tube further outward

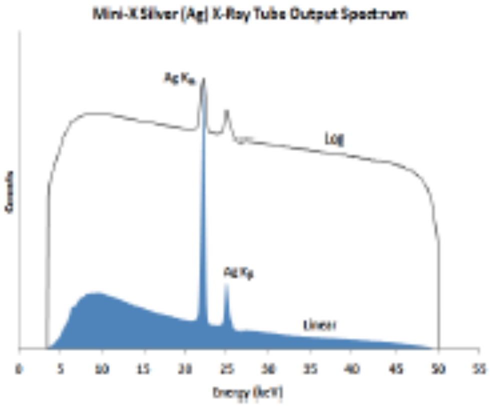
Significant reduction of material budget

Calibration of Internal VCAL Unit

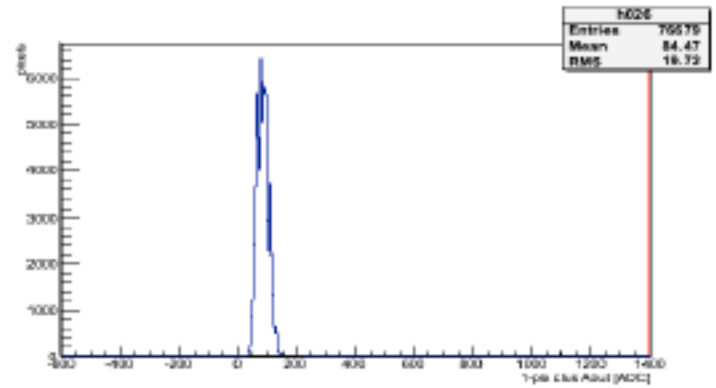


To how much deposited charge corresponds our internal unit "VCAL"?
In particular relevant for setting the thresholds properly

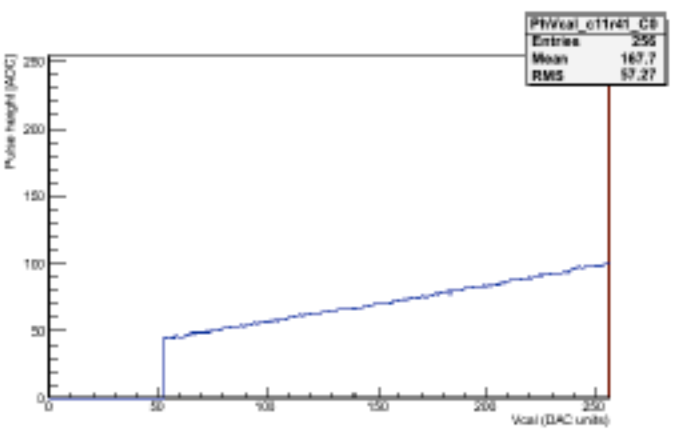
Spectrum Method



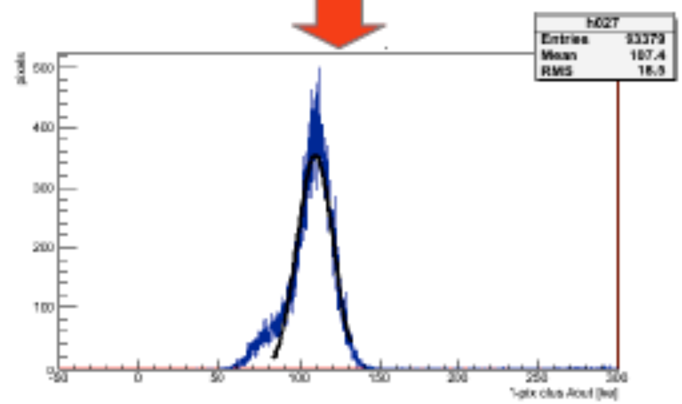
Choose specific energy with different targets



Measure ph-spectrum
in adc units

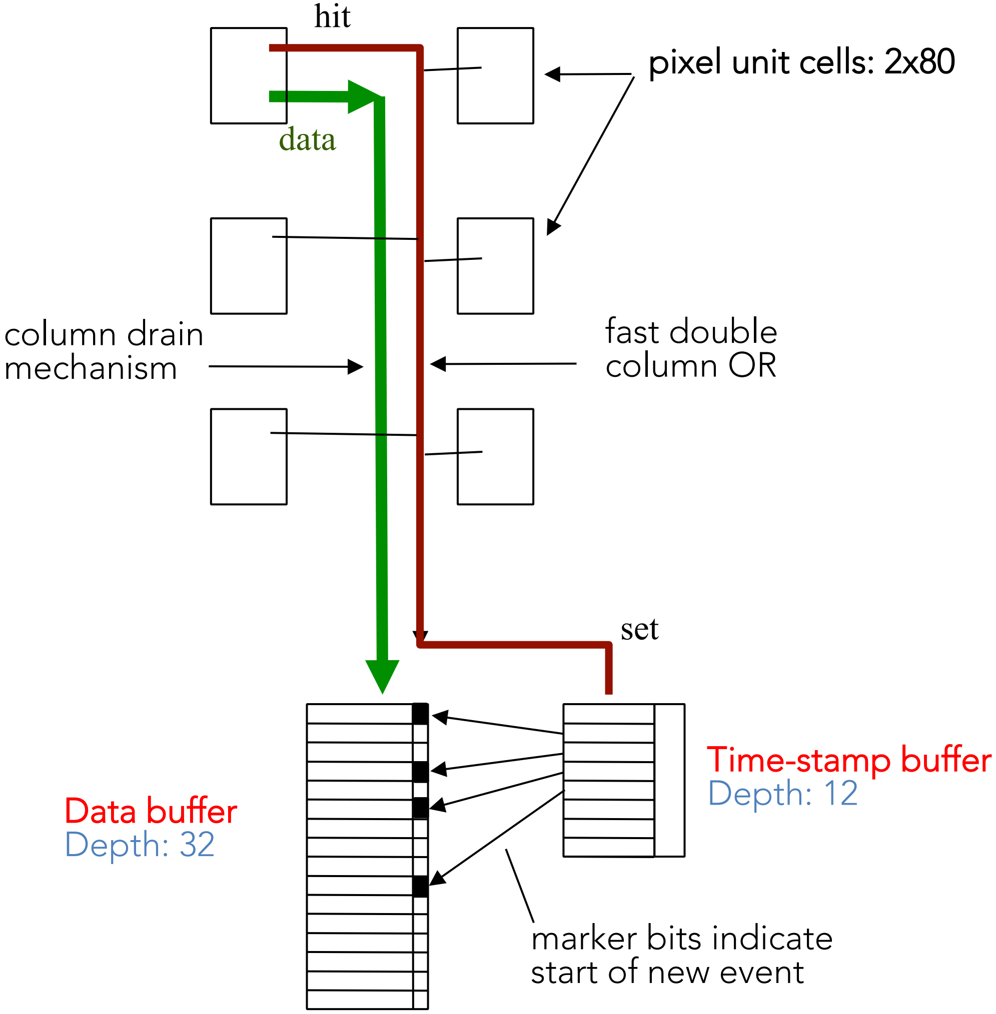


Do ph-calibration



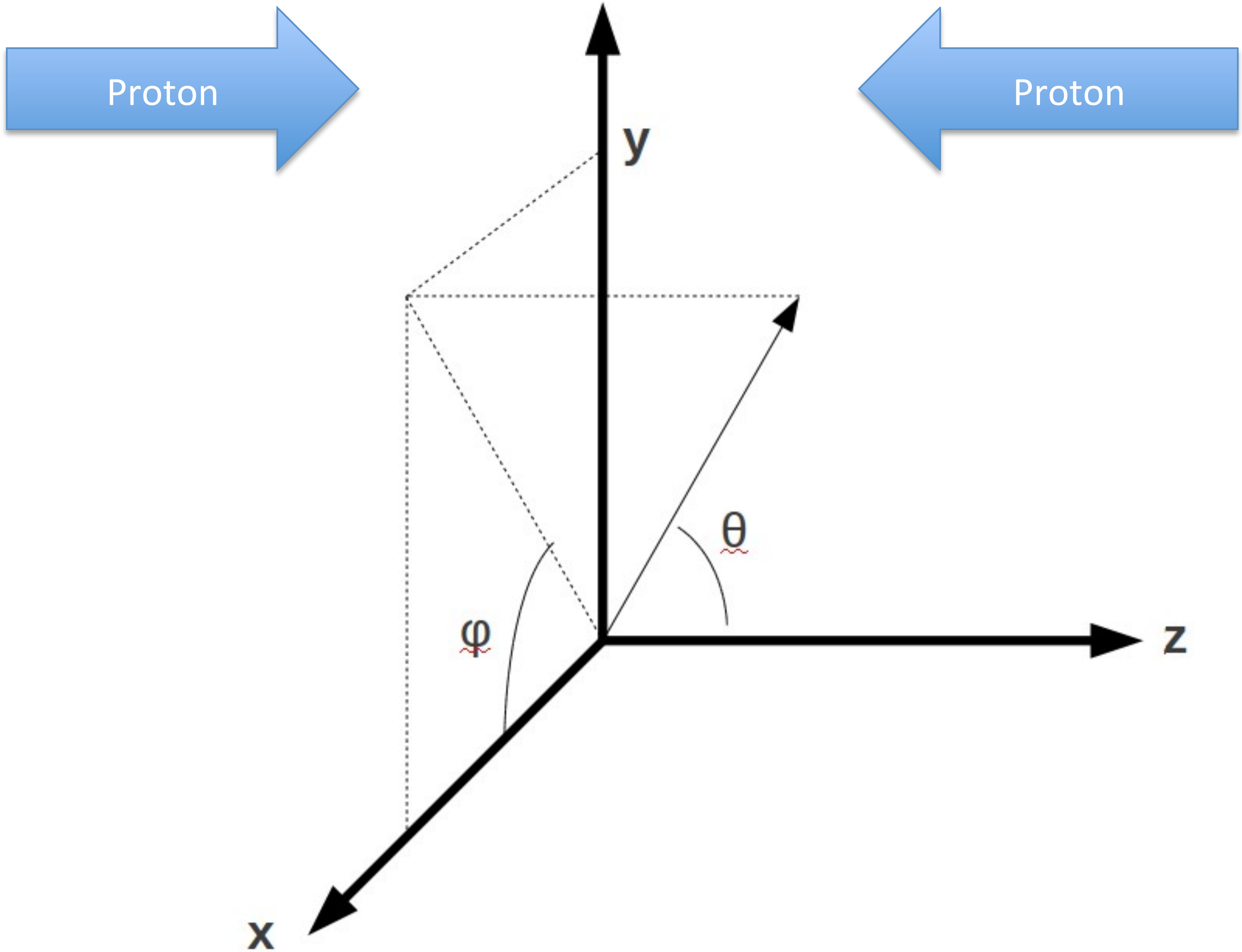
Get ph-distribution in vcal units

Double Column Readout



- Hit pixels send "OR" to the periphery
- Pixels are "frozen" and their hits are collected with a token that passes from pixel to pixel
- Hit-Pixel Addresses, pulse height and timestamps stored in DCol Buffers during L1 latency (~4μs=150 BC)
- If trigger validates a timestamp double column stops data taking and waits for readout token

CMS Coordinate System

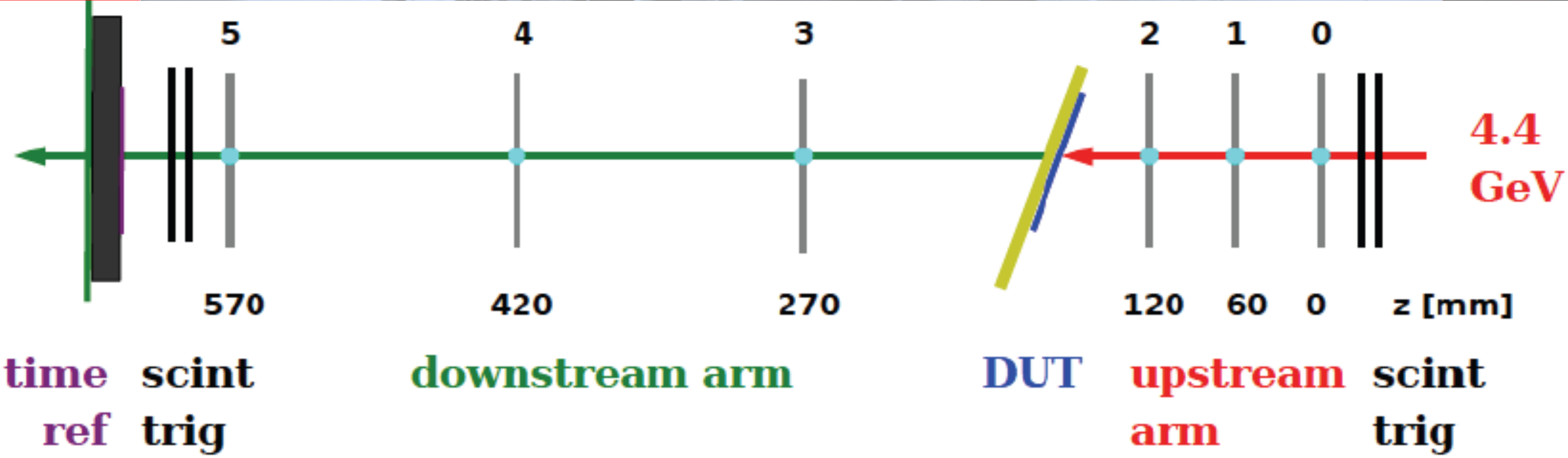


Data Rate Estimations

- Simulation with Pythia Z2 tune and GEANT4
- Assuming 24 bits per hit, 100 kHz level 1 trigger rate
- Peak luminosity = $2 \times 10^{34} cm^{-2} s^{-1}$, σ_{tot}=80mb, σ_{signal}=1.5mb, 25 ns BC

Layer radius	3 cm		7 cm	11 cm	16 cm
Pixel fluence [MHz/cm^2]	520		119	52	27
Hits / trigger / module	190		40	18	8.4
MBit/link/sec	435		118	66	45

1 ROC = 0.65 cm^2



eff = isolated telescope track with link to REF hit / DUT hit linked to isolated telescope track with link to REF hit

telescope track: tight matching cut 0.1 mm in x and y

isolation: no other telescope track within 0.3 mm at REF

REF link: tight cut 0.15 mm in x and y

DUT link: loose cut 0.5 mm in x and y

Tracker Radiation Dose

1 Gy = 100 Rad

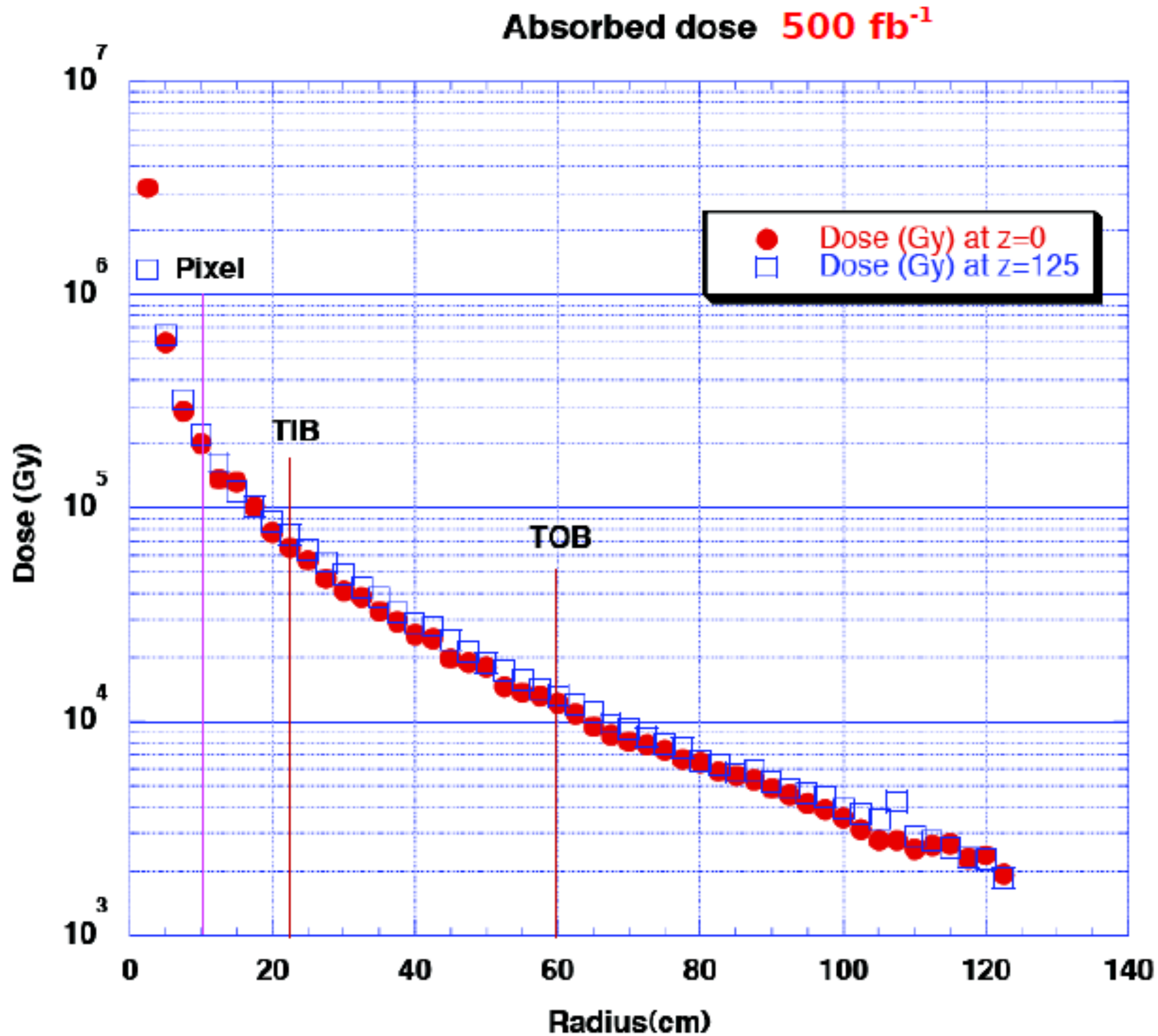
500 fb^{-1}

Layer 1: 200 MRad

Layer 2: 50 MRad

Layer 3: 20 MRad

Layer 4: 13 MRad



Pixel upgrade TDR 2012

Fluence:

1 MRad ≃ 3 10^{13}/cm^2 pions